Catalytic Converters for Small Spark-Ignited Nonhandheld Utility Engines

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Executive Summary

The attached discussion paper outlines several important factors that recent proposals for catalytic converters have not addressed. As the discussion paper indicates, there are a number of technical factors that severely compromise the possible benefit from catalytic converters on small engines. Those factors apply as much to higher-cost utility engines as they do to other small engines. Some of the main points presented below can be summarized as follows:

1. Nearly all gasoline-powered utility engines use manual chokes, which create very rich air:fuel ratios for engine starting under extreme operating conditions. If the choke remains on for any significant period of time, the rich air:fuel ratio will permanently deactivate the converter. (See pp. 1 - 3 below.)

2. Because they are air-cooled, utility engines pass relatively large quantities of engine lubricating oils to the exhaust stream, compared to water-cooled automotive engines. Contaminants in the lubricants (chiefly phosphorus and zinc) will poison the converter at rates far exceeding what is typical for automobiles and trucks. (See pp. 3 - 4 below.)

3. The ratio of exhaust gas passing through a converter to the volume of the converter is called the "space velocity" of the converter; for a converter to be effective, the space velocity must be relatively low. Because of the size of a utility engine exhaust system the catalytic converter volume can only be about 20 percent of the engine displacement. The converter will have very poor space velocity, compared to automobile catalysts. This imposes basic limits on the maximum efficiency of the converter and provides little or no margin to ensure effectiveness under in-use conditions. (See pp. 4 - 5 below.)

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Small spark-ignited nonhandheld utility engines (referred to in this paper as "small utility engines" or "utility engines") are general purpose engines under 25 horsepower (hp) in size. Most small utility engines are gasoline powered, and are designed for use in a wide variety of applications. These engines must be light weight, rugged, reliable, and suitable for use under varying operating conditions. The application of catalysts to utility engines is a recent endeavor. As explained below, differences in the design and operation of utility engines and automobiles prevents the direct application of current automotive catalysts to utility engines.

1. Background

The most obvious differences between an automotive engine and a utility engine relate to the basic design. Utility engines are generally air-cooled, with carbureted fuel control systems. Most utility engines do not have electrical systems, nor do they generally employ fuel injectors with feedback control systems for metering fuel into the engine. Instead, fuel is metered by a carburetor using a simple spring governor that maintains engine speed in response to varying loads by varying the throttle position.

Unlike an automotive engine, the same utility engine may be used in a wide variety of products and applications with varying duty cycles, and under a large range of operating conditions. The utility engine must operate acceptably in all of these applications. In addition, the engine is usually installed and used in equipment which is manufactured by companies unaffiliated with the engine manufacturer.

2. Basic Operating Conditions for Utility Engines

Utility engines are generally calibrated with richer air:fuel ratios. The richer mixture provides better governor stability, superior load pickup, and provides additional cooling for these air cooled engines. The use of carburetors in utility engines results in less precise control of the air:fuel ratio during engine operation. This less precise control of the air:fuel ratio is especially severe during transient or off-nominal conditions. For example, when rapidly idling down the engine, or under other similar transient conditions, the carburetor can not adjust the fuel flow as quickly as necessary to prevent a temporary decrease in the air:fuel ratio. Under these conditions, the air:fuel ratio can become as rich as 8:1.

Without an electronic feedback system and fuel injectors it is also necessary to employ a manual choke to ensure reliable engine starting at low temperatures. Utility engines are used in many applications (example: generators) where starting under harsh conditions is a necessity. The normal design goal used when designing a carburetor system is to ensure cold temperature starting capability down to -20 F. Under these conditions a choke is necessary to provide the rich air:fuel ratio and high intake manifold vacuum which ensure a combustible mixture is provided to the combustion chamber. Operating the engine with the choke left on will result in a rich air:fuel ratio approaching 8:1. This could occur when the choke is inadvertently left on after starting or when the choke is used for a hot start.

The use of fuel injection systems, oxygen sensors, and electronic feedback control have been investigated by small engine manufacturers. Addition of these fuel control systems in small utility engines has been found to increase the cost and complexity of a utility engine. These cost increases are unacceptable to most customers who use small utility engines.

Another general category of conditions which can result in rich air:fuel ratios results from engine misfire or incomplete combustion. On a single cylinder engine, engine misfire can occur sporadically. Potential causes include a fouled spark plug or dirty air cleaner. On a twin cylinder engine, misfire can occur continuously if the remaining cylinder continues to function acceptably. This could occur if a single spark plug or its associated wire were not functioning. Under these conditions, the uncombusted mixture of air and fuel is passed through the engine and directed into the converter. Again, these conditions can result in excess unburned fuel being fed to the converter.

When a utility engine converter suddenly encounters a rich air-fuel mixture, autoignition of the exhaust gas can occur. A rapid exothermic reaction quickly spreads from the catalyst. A visible flame can be generated which extends beyond the confines of the muffler and exhaust system. High temperatures above 2100 F are generated during the reaction. This autoignition sequence is described in Mooney et. al., “Exhaust Emission Control of Small 4-Stroke Air Cooled Utility Engines - An Initial R & D Report”, SAE Paper No. 941807, September 1994. This paper is attached (Attachment A). The reaction occurs under a variety of transient conditions, with all tested catalyst formulations, and with both aged and new catalysts.

The flame condition is particularly serious because the converter on most utility engines is in close proximity with both the engine and the equipment in which the engine is installed. On many applications, the converter would be relatively exposed to the environment. This creates the potential for igniting adjacent materials if the flame condition occurs. The flame condition described by Mooney et. al. remains a concern which has not been completely resolved. As the efficiency of the catalyst increases, an increased percentage of exhaust constituents is converted. This results in increased heat generation by the converter and also increases the susceptibility to the flaming condition.

The high temperatures which result from the rapid exothermic reaction exceed 2100 F. The temperatures can exceed the thermal deactivation temperature of the catalyst. At this thermal deactivation temperature, the catalyst manufacturer estimates that the active area of the catalyst will be reduced by 98 percent. In addition, repeated exposure to temperatures approaching the deactivation temperature also results in the rapid loss of catalyst efficiency. Thus, a single thermal excursion, or just a few less severe excursions, will deactivate the catalyst.

Finally, even after a utility engine is shut down, it is still susceptible to ignition of the exhaust gas. If a rich charge is introduced into a hot catalyst during engine coastdown, the exhaust can be ignited when it comes in contact with the hot surfaces of the muffler or catalyst. This condition, called "afterfire" or "afterbang," can damage the catalyst structure and the support mechanism and contributes to catalyst failure.

3. Irreversible Contamination ("Poisoning") and Oil Interference

The durability of catalysts in utility engines is a serious concern. Several features of utility engines make catalyst durability a more technically challenging goal compared to automobile applications. These features include the extreme temperature transients (discussed above), the oil carryover rates in utility engines, the limited space available for the converter, and the physical location of the converter relative to the engine.

One major cause of catalyst deactivation is poisoning of the catalyst. Poisoning occurs when the catalyst is contaminated with materials which inhibit the catalytic reaction. Phosphorous is a common catalyst poison of concern. Zinc, sulfur and other materials can also poison a catalyst. Phosphorous and zinc are contained in the lubricating oils used by consumers of utility engines. For example, Halvoline motor oil (a commonly used lubricating oil) contains approximately 1360 ppm phosphorous and 1460 ppm zinc. When oil is consumed by the engine, the phosphorous, zinc and other contaminants are carried through the exhaust and deposited in the converter. The greater the quantity of oil consumed by the engine, the greater the contamination of the catalyst.

Utility engines are air cooled. Like most air cooled engines, the cylinder bore distortion which occurs during operation is greater than in comparable water cooled engines. This cylinder bore distortion results in increased oil leakage around the cylinder piston rings during operation. This oil is combusted and the contaminants deposited on the catalyst. Typical oil consumption rates for utility engines are approximately 0.5 ounces per hour of operation. This oil consumption rate is an order of magnitude higher than a typical late model automobile.

The high oil consumption results in rapid poisoning of the catalyst. Testing results by a major catalyst manufacturer supplied to an engine manufacturer indicates that the catalyst rapidly loses a significant portion of its catalytic activity if oil carryover is limited to 0.16 ounces per hour of operation. This oil carryover limit is three times more stringent than the levels typically seen in small utility engines today.

The small utility engine industry has not been successful in addressing the problem of catalyst deactivation resulting from oil contamination. Higher oil consumption is an inherent feature of small air cooled utility engines. Operators of small engines typically use any available motor oils, even when advised against using specific motor oils (e.g. multigrade oils) which have been proven to increase oil consumption. Any changes in the requirements applicable to lubricating oils are likely to be driven by the automotive industry and not the small engine industry.

Quite apart from the problem of contamination in engine oil, gross oil intrusion in the catalytic converter can occur whenever portable equipment is tipped or inclined. Outdoor power equipment (tillers, for example) is regularly tipped or inclined during operation, when being maintained or inspected (blade change or sharpening on turf equipment), or when transported from location to location.

When engines and equipment are tilted there is often significant oil leakage directly into the exhaust system. The oil is then burned when the engine is restarted, sometimes resulting in a blue cloud of smoke. Unfortunately, this oil will also leave significant contamination on the catalyst, either through direct contact or through the combustion in the exhaust system. The oil contamination and catalyst deactivation problems described above will only be aggravated by this additional source of oil into the catalyst.

4. Space Velocities for Small Engine Aftertreatment

An additional technical difficulty faced when using catalysts in small engines is the lack of available space to size and locate the catalyst. A single small engine family is used in a wide variety of applications. It is important that the engine and its exhaust system be compact. Thus, if a catalyst is to be added to a small engine, it is imperative that it adhere to the existing space envelope to the maximum degree possible. Further, since there are so many applications, it is not feasible to design unique exhaust systems and catalytic converters for each application. Any catalyst selected will have to work in many or all applications.

Much of the volume of the exhaust system cannot be used for the catalyst because of other technical constraints. Placing the catalyst too near the exhaust system exit increases the propensity for flaming and autoignition of the exhaust. Locating the catalyst too far upstream in the muffler will allow insufficient exhaust gas mixing and exhaust flow damping to achieve optimum catalyst efficiency.

The limited space available for a converter results in a much smaller converter volume relative to the engine displacement than is currently used in automotive applications. The limited space available in many applications for a typical Class II utility engine results in a catalyst volume that is a small fraction of the engine displacement. In current automobiles the catalyst is approximately equal in volume to the engine displacement. Thus, a small engine catalyst can be roughly five times smaller than an automotive catalyst relative to the engine size.

The limited size of the catalyst results in a much more demanding environment. The volume of exhaust gas passing through a given volume of the catalyst (the specific throughput or "space velocity") will be much greater. Based on the relative size alone, a given volume in the catalyst of a small engine would be exposed to approximately seven times the exhaust of the same volume in an automotive catalyst. Unfortunately, the higher average operating speeds of utility engines will also mean that the specific exhaust rates are higher compared to automotive engines. Small engine catalysts have throughput rates which are more than an order of magnitude higher than automotive catalysts. The space velocity of a typical small engine catalyst will range from 250,000 to 1,500,000 hr^{-1}. The space velocities used on automobile catalysts range from 18,000 to 108,000 hr^{-1}.

The higher throughput or “space velocity” under which the small engine catalyst operates results in a more severe condition. With more than ten times the exhaust passing through a specific volume of the catalyst the catalyst will be more susceptible to poisoning. For a given concentration of contaminant in the exhaust, there will be greater than ten times the quantity of the contaminant passing through a given volume of the catalyst. This leads to earlier and more severe poisoning of the catalyst in a small engine compared to an automotive catalyst exposed to the same exhaust composition.

Small engine exhaust is far more likely to have higher concentrations of both contaminants and exhaust constituents requiring conversion. The higher contaminant concentrations are the result of the higher oil consumption rates described above. The higher oil consumption rates, combined with the lower total exhaust gas volume from a small engine, results in higher contaminant levels. The higher contaminant levels, combined with the higher specific throughput in the small engine catalyst, lead to the faster deterioration of the catalysts used on small engines

5. Engine Design Constraints

Small engines have higher concentrations of exhaust gas constituents requiring conversion. This is a result of the richer air:fuel ratios required in small engines for successful operation and engine cooling. A small engine often has in-use HC emissions of between 1000 and 3000 ppm. The compact size of the catalyst, the high specific throughput, and the high concentration of emission constituents result in high heat generation rates and high temperatures in the catalyst. These high temperatures can exceed 2100 F during transients (see discussion above). These temperatures are well above the temperatures encountered by today’s small engine exhaust systems.

These temperatures would be even higher if small engine designers attempted to achieve catalyst efficiencies approaching those of automotive catalysts. The high exhaust gas concentrations and the high space velocities would create excessive heat loads and temperatures. Thus, it is necessary to limit the initial catalyst efficiency to protect the engine and exhaust system.

Unlike a water cooled engine, a small air cooled utility engine has limited means for removing the additional heat and high temperatures which result from the catalyst. The additional heat load presents a problem in ensuring the structural integrity of the catalyst as well as the emissions durability of the catalyst. The emissions durability effects (thermal deactivation) of the elevated catalyst temperatures have been discussed above.

The structural integrity of the catalyst and exhaust system is at risk from the elevated temperatures during rich air:fuel ratio transients and as a result of the higher temperatures which will occur regularly during operation. The thermal energy from the exothermic catalytic reaction must be dissipated within the space available for the current engine and exhaust system. Unlike water cooled engines which can vary the convective heat transfer rate through the use of thermostats and variable coolant flow, an air cooled engine must rely on the available radiative and convective air cooling capacity of the engine. The limited available space makes any significant increase in this capacity problematic.

The high catalyst temperatures (above 2100 F) which are encountered by the exhaust system result in mechanically stressing the catalyst structure, the mounting hardware, and associated exhaust system components. The mechanical loads which result from the high temperatures can reduce or eliminate preload in fasteners, and loosen other mechanical fittings. An indication of the degree to which these components are stressed during rich air:fuel transients is the cherry red color of some of the exhaust system components.

The need for a compact and self contained exhaust system on small engines results in the mounting of the exhaust system and catalyst directly to the engine. The catalyst is usually located within 4 inches of the engine block. The close proximity of the engine to the catalyst aggravates the mechanical loads to which the catalyst is subjected. Engine vibration is directly transmitted to the catalyst as there is no significant distance through which the engine vibration can be damped and reduced. Engine vibration is especially significant on small utility engines because many are single cylinder designs; there are no other cylinders to balance the combustion firing cycle. Thus, the magnitude of the engine vibrations the catalyst is subjected to are much greater than in an automotive catalyst. Long term exposure to these thermal excursions, the resulting high temperatures, and the significant engine vibration loads will increase the susceptibility of the converter and associated exhaust system components to mechanical failure.

Many Class II engines are currently sold by the engine manufacturer without an exhaust system. This is due to the necessity of integrating the exhaust system into the specific equipment application. Multistage certification of incomplete engines would be required to address the dozens of potential exhaust system configurations from a single engine family.

Conclusion

The small utility engine presents many technical challenges to the successful application of catalysts to reduce exhaust emissions. The air cooled engine design of the engine results in greater oil carryover to the catalyst; this in turn results in rapid contamination of the catalyst. Air cooling also prevents the efficient removal of excess heat generated by the catalyst. Carbureted fuel delivery systems are necessary because many engines do not have electrical systems, and the expense of a fuel injection system is too great. The rich air:fuel ratios which can occur result in temperatures approaching or exceeding the thermal deactivation temperature of the catalyst. Utility engines must have small catalysts to fit into existing products and to accommodate a wide variety of intended applications; the small size results in high exhaust gas throughput and rapid poisoning of the catalyst. The compact design of small engines also necessitates attaching the catalyst and exhaust system directly to the engine, subjecting the catalyst to high vibration loads. These technical problems make the commercial application of catalysts to small utility engines problematic.